

THE INTERNATIONAL SPACE STATION (ISS) SOLAR ALPHA ROTARY JOINT (SARJ): MATERIALS & PROCESSES (M&P) LESSONS LEARNED FOR A LARGE, ROTATING SPACECRAFT MECHANISM

Dr. Johnny L. Golden, Consultant
16346 Havenpark Ct, Houston, TX 77059 USA
johnny.l.golden@boeing.com 832-723-6276

ABSTRACT

The International Space Station (ISS) utilizes two large rotating mechanisms, the solar alpha rotary joints (SARJs), as part of the solar arrays' alignment system for more efficient power generation. Each SARJ is a 10.3m circumference, nitrided 15-5PH steel race ring of triangular cross-section, with 12 sets of trundle bearing assemblies transferring load across the rolling joint. The SARJ mechanism rotates continuously and slowly – once every orbit, or every 90 minutes. In 2007, the starboard SARJ suffered a lubrication failure, resulting in severe damage (spalling) to one of the race ring surfaces. Extensive effort was conducted to prevent the port SARJ from suffering the same failure, and fortunately that effort was ultimately successful in also recovering the functionality of the starboard SARJ. The M&P engineering function was key in determining the cause of failure and the means for mechanism recovery.

From a M&P lessons-learned perspective, observations are made concerning the original SARJ design parameters (boundary conditions), the perceived need for nitriding the race ring, the test conditions employed during qualification, the environmental controls used for the hardware preflight, and the lubrication robustness necessary for complex kinematic mechanisms expecting high-reliability and long-life.

1. INTRODUCTION

As the International Space Station (ISS) surpasses 15 years of continuous habitation by over 200 crew members from 15 countries, it can generally be observed that the vehicle has performed exceedingly well. However, one of the difficulties experienced and overcome by the ISS program team was the anomaly with the starboard Solar Alpha Rotary Joint (SARJ).

The SARJ is a mechanism that allows continuous orbital-rate sun-tracking rotation of the outboard trusses and solar arrays of the ISS. Two SARJ mechanisms were installed on port (activated December 2006) and starboard (activated June 2007) locations on the ISS truss. The SARJ serves as the structural joint between the ISS inboard and outboard trusses, via twelve trundle bearing assemblies (TBAs). The trundle bearings straddle between two (inboard and outboard) triangular cross-section race rings. TBAs are nominally mounted to the stationary inboard ring, and their rollers track against the three surfaces of the outboard race ring. These rollers are pre-loaded against the race ring surface by the TBA to allow them to react to expected ISS structural loads. TBAs are designed for individual on-orbit replacement in case of bearing failure or roller damage, and the rollers (made of 440C with gold ion-plating) were intentionally

designed with lower hardness than the non-replaceable race rings (plasma nitrided 15-5PH steel). The SARJ is driven by redundant Drive Lock Assemblies (DLAs) that interface with an integral bull gear on the race ring via a motor-driven pinion and two groups of three supporting rollers. Each DLA is controlled by a Rotary Joint Motor Controller (RJMC), which, in conjunction with processors in the ISS computing infrastructure, performs closed loop control of the joint's motion. SARJ system health and status data are relayed by the processors to the ground in the ISS telemetry stream.

1.1 Issue

In early September 2007, 2 months after activation, the starboard SARJ reported that drive command current started increasing from a nominal peak value of approximately 0.2 amps to a peak value of approximately 1.2 amps in a period of 6 weeks. As the current increased, onboard accelerometer measurements and visual observation of increased vibrations on the ISS structure were a concern. Shortly after these increases in current and vibration, the decision was made to stop the starboard SARJ from autotracking and avoid further rotations until the cause of the current increase could be determined. Operation of the port side SARJ was nominal and was not interrupted.

1.2 Investigation and Significant Findings

After an extensive investigation by the NASA/ industry/academia SARJ Recovery team, the following significant findings were reported [1].

1.2.1 Drive current and vibration increases on-orbit were a result of damage to one surface (the “outer canted” surface) of the outboard race ring.

Inspections and cleaning of the race ring were conducted during multiple extravehicular activities (EVAs). Visual inspection showed significant debris covering one of the starboard SARJ race ring surfaces and evidence of surface pitting and compressive agglomeration of debris. Roller mechanism and drive control system interaction with the race surface in this condition and debris entrained into the TBAs explained the current and vibration signatures.

1.2.2 Damage to the race ring was characterized by delamination/spalling of the nitrided hardened surface material from the core 15-5PH steel.

Returned samples of the debris was principally 15-5PH nitride material, with some traces of gold and lubricant that was later identified as Braycote 601. 15-5PH particles were almost exclusively nitrided, and chips bearing manufacturing tool marks (showing the original race ring surface) were of thicknesses comparable to the expected nitride depth.

1.2.3 Unexpected metallurgical surface structure was identified in race ring witness coupons and test samples.

Metallurgical analyses conducted on both port and starboard flight hardware witness specimens revealed that the surface contains a residual white layer, which is normally required to be removed as part of the nitride process. In addition, the surface of the case (the upper 0.003 inch) in witness coupons also contains intergranular networking in excess of engineering requirement.

However, testing indicated that the white layer was not the initiation source of the observed degradation.

1.2.4 Metallography indicates that the concentration of Discontinuous Intergranular Separations (DIGS) in the starboard SARJ race ring coupons is 5 to 6 times higher than those observed in the port SARJ.

This difference in defect concentrations may account for or contribute to the differences in damage rate and damage propagation observed between the port SARJ and the starboard SARJ race rings.

1.2.5 Force balance analysis of the TBA design showed a susceptibility to roller tipping and edge loading.

A simple free-body diagram shows that any roller mistracking tendency with greater than a 0.4 coefficient of friction (COF) creates an overturning moment that rotates the trundle bearing roller about its camber axis, causing the roller to roll on its edge. Since the rollers are not self-aligning, small misalignments (tenths of degrees) will result in some mistracking with a magnitude dependent on as-built manufacturing tolerances and direction of rotation.

1.2.6 Race ring/roller friction is not adequately controlled in the SARJ design to prevent roller tip induced edge loading.

Testing showed that the TBA roller will tip if the COF is above the critical value, and the only specified race ring interface friction control was gold plating applied to the roller. Records review and testing show that the gold plate was too thin to preclude oxidation and debonding, and its durability in the SARJ application was not demonstrated. TBA misalignment analysis and test data from traction curves indicates that without gold, the race ring roller interface COF approaches or exceeds the critical 0.4 critical tipping value.

1.2.7 Edge loading of the roller results in high contact and subsurface race stresses.

The TBA rollers were not crowned, and specialized codes were developed to analyze the non-Hertzian field stresses encountered at the roller edges. Analysis shows that with a roller tipped on edge, the resulting contact pressure and shear traction result in sub-surface shear stresses that could damage the starboard SARJ race ring in a manner consistent with the observed degradation.

1.2.8 Unexpected surface lubrication was identified on the Port SARJ.

During on-orbit extravehicular activity (EVA) inspections, evidence of Braycote 601 (lubricant used internally in TBA bearing packs) was noted on the port SARJ race surfaces. Though not a root cause contributor, oil migration does potentially provide a tribological difference between the port and starboard SARJs.

In summary, given the on-orbit observations, review of build and test records, tests, analyses, and simulations performed to date, a most probable SARJ anomaly root cause statement can be made. The kinematics of the TBA and DLA mechanisms require that the roller thrust loads (related to friction coefficient and mistracking angle) be controlled to ensure stable roller line

contact with the race ring surfaces; no small feat for rollers following a conical surface. Inadequate lubrication of the roller/race ring interface combined with roller mistracking angles still within specification resulted in thrust loads high enough to cause at least some of the TBA or DLA rollers to edge load as the SARJ rotated. When a roller is edge loaded, the preload on that roller is concentrated on a reduced contact area, resulting in high contact stresses and shear stresses at the case / core interface. These stresses exceed the allowable bearing strength capability of the race ring case and core, leading to brittle fracture and spalling of the nitrided layer from the starboard SARJ race ring.

2. MATERIALS & PROCESSES LESSONS LEARNED

The SARJ is foremost a mechanism, with all the structural (loads, fracture, and dynamic) analysis one would expect for deployment on a human-rated spacecraft. But the M&P engineer provides a critical supporting engineering function to the mechanism design team, called on for input into materials selection and finishes, quality assurance testing, qualification test conditions, hardware environmental controls during storage, and expected reliability/durability of various design options. The ISS SARJ experience serves as a great example of how all of these areas can be examined as part of a lessons learned discussion, certainly applicable to the development and deployment of the next generation of large, rotating mechanisms for spacecraft, and likely applicable to other non-spacecraft mechanisms as well. What follows here is only an excerpt of the extensive work conducted and reported by the SARJ Recovery Team [1], but is focused on aspects intersecting with the M&P function responsibilities and lessons learned. As a leading member of that team, some of these observations herein are augmented by personal recollections from the successful recovery effort.

2.1 Design Boundary Conditions

One of the unusual characteristics of the overall ISS program is that it was a reorganization of an extensive predecessor program, Space Station Freedom (SSF). Extensive work had been conducted during SSF on all major systems design, including the SARJ, and ISS program was intent on making maximum use of prior design in order to accomplish very aggressive cost and schedule targets. This is not to say that SSF design was accepted without analysis and assessment. On the contrary, the more international character of the ISS program, the actual formalization of an assembly sequence coupled with an early assured science capability such that ISS could evolve through assembly while still being operational required that the ISS be critical of all systems designs (a process called “grand-fathering”). However, there was obviously a limit on the extent of requirements review and systems analysis that could be conducted during “grand-fathering”.

In the initial failure analysis discussion by the SARJ Recovery Team, many tribology experts were surprised that the only lubrication of the interface between the nitride 15-5PH steel race ring and the 440C TBA rollers would be a 1500 – 2000 angstrom thick layer of gold. Other mechanisms utilizing nitrided stainless steels typically use grease, with the grease variety controlled by the loading expected and the use environment. Members of the Team who had been involved with SARJ since its early design during SSF recalled design review discussion of the need to avoid the use of grease for lubrication. The reasoning was thought to be excessive contamination potential for EVA crew working on or in the area of the SARJ. However, this constraint was never formalized in system requirements documentation.

It is interesting, then, that since the primary cause of the starboard SARJ race ring failure was loss of friction control, the remediation of the port SARJ and the recovery of the damaged starboard SARJ were accomplished through the application of a vacuum-stable grease for lubrication. The grease approach was accepted without apparent reservation by ISS EVA crew systems, and the SARJ mechanisms have been autotracking continuously and largely without issue ever since. The M&P function is typically a key player in establishing contamination control requirements. In this case, the contamination risk associated with the use of grease in the SARJ was not critically assessed or documented in design requirements.

M&P Lesson Learned: Be critical of design constraints, especially those which place the design outside of typical experience, and assure that the constraint and its rationale is documented in system requirements.

2.2 The Need for Nitriding and Its Quality Evaluation during Production

Early in the SSF SARJ design, the decision was made to nitride the race ring. This nitriding was principally required to harden the surfaces of the bull-gear teeth on the race ring, interfacing with the pinion drive system, but nitride was also applied to the roller contact surfaces. Hardening the race ring roller contact areas was intended to force wear of the mechanism to the TBA roller surfaces, since the TBA components are replaceable on-orbit and the race rings (attached to primary truss structure) are not. This hardening of the race ring roller surfaces was done without recognizing that the sole friction control for the rolling interface was an exceedingly thin layer of gold now located on the sacrificial wear surface, where the lubrication would be certainly lost.

In retrospect, especially when considering that the damaged starboard SARJ functionality was recovered after having apparently spalled the entire 150 μm (0.006 inch) nitride layer from the outer canted surface, one could call into question the perceived need for nitriding the race ring to prevent surface wear during operation. Certainly the failure mode of the mechanism after friction control was lost would have been different if the case layer had not existed and spalling of the race ring surface had not been possible.

Once the nitriding decision was made, metallographic examination of nitride control coupons was required to ensure adequate nitride depth and intergranular networking controls. Independent examination of the nitride witness specimens (properly retained by the original SARJ contractor) by the SARJ Recovery Team found intergranular networking in excess of engineering requirements, and found DIGS – separations within the nitride case which could act as crack initiation sites should loading conditions in the mechanism be able to focus there (such as roller sliding). Neither the networking nor the DIGS were recognized during SARJ race ring manufacture. The metallography originally conducted did not properly identify the intergranular networking and appears to have obscured the presence of DIGS.

M&P Lesson Learned: The need for nitriding beyond the bull gear teeth on the race ring is, in retrospect, unsubstantiated. Although nitriding of the race ring would still have been required (no small feat for a 10 m circumference detail), the additional processing of removing (or at least attempting to remove) the nitride white layer from the canted surfaces and honing of the Datum-A surface would not have been required. Be mindful of the unintended consequences of “make it better” decisions in design, in this case, attempting to force rolling surface wear to the TBA

rollers, when the design could adequately accommodate a significant amount of wear without nitriding the roller contacts on the race ring.

Be critical of metallography, and assure best practices are used to avoid distortion or obscuration of features in metallographic cross-sections.

2.3 Qualification Test Conditions

Original qualification of the roller-to-race contact surfaces was conducted as part of the Pinion Life Test (PLT). The SARJ Structural Test Article was used for the PLT using a mechanical drive system with flight fidelity pinion, TBAs, and race ring. The primary purpose of the test was to demonstrate life margin for an un-lubricated pinion on a nitrided bull gear. However, the PLT was also used to demonstrate trundle bearing operation and system level 10-year operational life. The test was conducted under ambient conditions in air and in an accelerated manner. As the SARJ operational environment is in vacuum, the friction between rolling elements (TBA rollers and race ring) would be expected to potentially be much higher in operation. The gold layer on TBA rollers (the sole friction control between rollers and race ring) was completely absent at the end of the test. Post-test photos also showed substantial debris caked to the chamfered edges of the rollers, just outside of the rolling contact, suggesting the presence of a conglomerating agent. Though not recognized at the time, the SARJ Recovery Team believes that grease within the TBA rollers leaked out, largely because of the accelerated speed used to conduct the PLT, and that the PLT was essentially conducted with a grease (rather than gold) acting as lubricant between the race rings and the TBA rollers.

M&P Lesson Learned: Qualification testing of large complex mechanisms is an area of intense debate between engineers, especially when it comes to life testing of 10 years or more, and goes way beyond the typical scope of M&P design responsibility. However, M&P engineering must participate in the definition of and assess qualification testing conditions. Clearly, cost and schedule are significant factors in the qualification testing decision process, but M&P must bring critical thinking to the table. The PLT results fooled ISS mechanisms engineering into thinking friction was understood for the SARJ, when on closer examination, it was actually showing that we had a mechanism which tended to roller tipping and that friction was being controlled by inadvertent grease leakage from within the TBA rollers. Obviously, running the PLT under more flight-like conditions (in vacuum and at a lower speed) would have increased test costs substantially. Nevertheless, the PLT test and its implications as a system-level operational-life test were not adequate to the task and mislead system managers.

2.4 Hardware Storage Controls

After ion gold plating of the 440C TBA rollers, the TBAs were assembled and not required to be kept under any specific environmental controls other than for visibly-clean contamination control. Ultimately, the TBAs were integrated into the SARJ assemblies, at which point again only contamination controls were specified. The ion gold plating specification identified an adhesion requirement to demonstrate adequate (tape test) bonding of the gold to substrate. This adhesion of gold to the roller substrate is an essential condition for gold's effectiveness as a solid transfer-film lubricant in the SARJ application.

It was observed by the SARJ Recovery Team that gold adhesion on flight spare TBA rollers exhibited poor adhesion and complete loss of gold in some areas. Demonstration articles were produced using the original ion gold plating process, which included demonstration of compliant adhesion. The Team then exposed the demonstration articles to an accelerated environmental condition (95% relative humidity and 125°F) to simulate years of the assembly and storage environment. Gold adhesion loss became widespread and showed very similar flaking characteristics to that seen with the flight spare TBA rollers. The team assessment was that the gold plating was so thin as to not provide an absolute barrier between the environment (water, oxygen) and the 440C substrate. The substrate reoxidizes (it is plasma deoxidized to prepare the surface during the ion gold plating process), undercutting the gold adhesion. As a result, even if gold had been adequate to control friction in the kinematic environment of the SARJ roller contact (and some SARJ Recovery Team testing indicated that it could have), the loss of gold adhesion to the TBA rollers because of handling and storage environment meant that the lubrication approach was doomed to fail.

M&P Lesson Learned: The SARJ mechanism was designed to operate in vacuum, and materials and finishes decisions must first consider the operating environment for the hardware. But the hardware also has to get to space and will be exposed to nominal atmospheric conditions throughout that time and potentially be exposed to seacoast environmental conditions. In the case of the SARJ mechanisms, both spent years on the ground longer than was intended – caused by the stand-down in ISS construction because of the Columbia accident and the time it took for the Orbiter fleet to return to flight. But even without the unplanned delays in the ISS assembly process, there was nothing in the engineering requirements for the TBAs to provide a dry, inert atmosphere to protect gold adhesion to the rollers. In fact, adhesion loss on TBA rollers was observed on the flight hardware, but again the PLT experience was used, this time as evidence that gold loss was to be expected and that the system passed the life test anyway.

Although there is a strong tendency to design strictly for the hardware's operational environment (in the SARJ case, space vacuum), the M&P engineer must also consider the effects of the ground environment on materials. A more robust finishing approach for accommodating the ground environment, or for a temporary off-nominal environmental condition, could be a very effective insurance policy against the degradation of functional finishes. The only alternative is rigorous environmental controls which may be very difficult to employ for large mechanisms.

3. SUMMARY

The hazard of conducting a “lessons learned” analysis is that it can appear overly critical; as in “how could the engineers involved have missed the opportunities described in this paper to avert the starboard SARJ failure?”. Since it is always easier to look back at the facts after known consequences than to foresee consequence when first making observations (coupled with the cost and schedule pressures which were manifest during the early phase of the ISS program), the focus here must be on providing example situations where the opportunities (for whatever reason) to increase the robustness of the SARJ design were missed. Knowledge of how and why we have failed in the past aide the M&P engineer in being more critical, more objective, in the face of cost/schedule pressure to assure that prior errors (missing intergranular networking and DIGS) are not made and that project/program managers are properly informed of their risks.

Robustness of design is another of those general topics, like qualification testing of long-life mechanisms, which will continue to be argued among engineers. It is clear that the lubrication system for the SARJ was not adequate to control friction, given the kinematics involved with this mechanism in its actual operating environment (root cause). Lubrication margin is qualitative, and the only opportunity to examine that effect for the SAJR example was during the PLT. That test was deemed successful, without really understanding what the test actually showed, and that success was then used to provide rationale for accepting lubrication system discrepancies observed later. The M&P engineer must look for ways incorporate robustness while controlling cost – often easier said than done!

The perceived need to use a lubrication approach outside of typical experience for the materials involved (affecting design), and a system life test where the implications were not actually understood (qualifying the design) are key SARJ lessons for the M&P engineer, concerning future large spacecraft mechanisms.

4. REFERENCES

1. Enriquez, C., et al., (including Golden, J.L.) International Space Station Program, Type 4 Document, D684-13412-01, International Space Station Solar Alpha Rotary Joint Anomaly Report, September 15, 2009.